CURRENT EXPERIMENTAL AND NUMERICAL ISSUES IN MASONRY RESEARCH

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ABSTRACT

The paper addresses the possibilities and research needs with respect to advanced testing and numerical analysis of masonry structures, with a focus in cyclic behaviour. A complete masonry characterization is sought, in terms of modern deformation controlled test set-ups, which is a key aspect for modern, non-linear, computer simulations. In addition, the aspects related to masonry innovation and to construction needs are also addressed.

1. INSTRUCTIONS

Masonry and timber are probably the oldest building materials, being present in most of the existing built heritage. Strangely these materials receive little attention in the curricula of Civil Engineering graduations in developed countries. With the appearance of steel and concrete as the key buildings materials of the 20th century, modern structural engineers possess a scarce knowledge about traditional materials and techniques. The lack of knowledge on traditional materials and techniques is a strong bias in the rehabilitation of existing constructions and precludes the correct assessment of safety. For new constructions, the lack of knowledge usually results in these traditional materials not being considered as an option in the preliminary design phases. Nevertheless, the trend to sustainable construction and eco-efficiency gives rise to a renewed interest in timber and masonry. Masonry itself is rather eco-efficient when compared with competing technologies such as concrete or steel. The energy required to produce clay brick is only 2.8 MJ/kg, whereas concrete requires 8.5 MJ/kg and steel requires 43 MJ/kg [1]. Other relevant characteristics of brick include durability, fitting architecture trends, nice looking and ageing, long lasting and virtually maintenance-free. Masonry structures are also easier to demolish and components are easier to recycle.

The present paper addresses the issues related to the advanced knowledge of the constitutive behaviour of masonry and the computer simulation of the mechanical behaviour (i.e. structural analysis). Time shows that many historical masonry constructions collapsed due to accidental actions, like earthquakes. Nevertheless, modern engineered masonry cannot be compared with old traditional masonry. After the Second World War, the solutions and building technologies changed rapidly, being replaced by new solutions, sometimes independent from the local conditions. In terms of structure, the floor structure has been replaced by reinforced concrete solutions and the vertical elements have been mostly replaced by a framed structure, adding masonry wall infills. This evolution, see Figure 1, lead to a market loss for bricks and blocks but it is noteworthy that countries with severe seismic activity like Italy or United States, still make extensive use of structural masonry. Load bearing masonry, especially with rendered blocks of clay or concrete, is mostly used in developed countries in new small housing buildings of no more than two or three floors. Clay brick is mostly used in housing and concrete block is more common in commercial buildings, especially when it is necessary to build very high or very long walls, being the hollow concrete block usually more prone to vertical reinforced solutions.

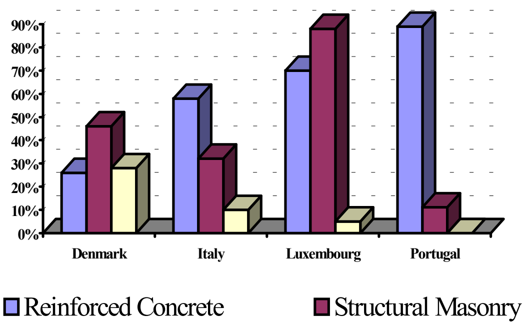


Figure 1: Comparison of structural solutions for buildings adopted in some European countries [2-5].

Presently, the type of structure most used in Portuguese buildings is a reinforced concrete frame infilled with non-load bearing masonry walls. The masonry works, including rendering, are estimated to account for 13 to 17% of the total cost of the building [6]. The fact that approximately one sixth of the cost of a building is due to partition walls seems to indicate that the adopted type of construction in non-economical.

Here, the aspects of advanced testing and numerical analysis of masonry structures is addressed. The main focus is on the cyclic behaviour, which is a subject that has received only limited interest from researchers. The lack of experience in this field is notorious in comparison with more advanced research fields like concrete, soil, rock or composite mechanics. It is also shown that a complete set of displacement-controlled tests needs to be carried out, in order to obtain the properties necessary for advanced numerical models. With this information, sophisticated and robust models for masonry structures can be made available. Finally, to introduce also the issue of industrial and construction needs, a short review of masonry innovation is also provided.

2. INNOVATION IN MASONRY STRUCTURES

The lack of codes and standards for masonry, besides technological and architectural motivations, constituted until recently, the main reason for not using masonry as a structural material. The criteria for masonry design have been mostly empirical and intuitive, based on approximate analysis and an outdated format. Recently, at European level, the technological and mechanical aspects of structural masonry have been regulated with Eurocode 6 – Design of Masonry Structures (EC6) [7] and Eurocode 8 – Earthquake Resistant Design of Structures (EC8) [8].

2.1. Masonry and earthquakes

Structures in seismic regions should be designed and constructed in such a way that local or general collapse are prevented, and the costs of damage and limitations of use are not disproportionate high in comparison with the costs of the structure itself. "Heavy and large walls, built perpendicular and with good foundations, return to its original position, always... and suffer less damage if well connected". These preliminary observations of Pirro Ligorio in the 16th century demonstrate the concern of safety with respect to seismic actions [9]. In particular, an ideal system for anti-seismic construction is proposed, see Figure 2, stressing the need for bracing between structural elements and the significant role of arches and vaults in order to obtain a ductile structural behaviour.

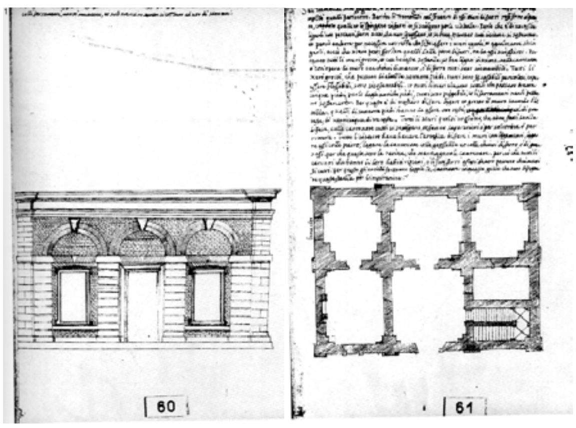


Figure 2: Façade and plan of the seismic resistant house proposed by Pirro Ligorio.

The effect of earthquakes on structures, as it is known today, depends on aspects such as magnitude and dynamic characteristics of the earthquake, location of the construction, geological conditions of the soil, shape of construction, foundations, construction material, adequate design provisions, detailing of the structural elements, etc. But the main influence factors are: (a) regularity in plan and elevation, and (b) use of materials adequate to provide the necessary resistance to the seismic action. Unfortunately, numerous constructions did not comply with the above requirements. In Portugal, in 1755, the sadly well-known earthquake of Lisbon illustrated the effects of a shake of large intensity and lead to the development of a new type of ductile and "reinforced" construction: the Pombaline cage, see Figure 3.

(a) (b)

Figure 3: The example of Lisbon (Portugal): (a) image of the destruction of 1755 and (b) the new composite wood-masonry walls.

Other solutions have been proposed – e.g. ties, iron bars in the joints, interlocking units with dowel effect, etc. – aiming at increasing the performance of masonry under seismic actions. Nevertheless, long return periods of earthquakes for the same location, lack of technical and scientifical knowledge, budget constraints of the owners and the lack of adequate provisions in regulations and codes, resulted in devastating effects of earthquakes on masonry constructions. In the beginning of the 20th century, three large earthquakes of considerable magnitude, see Figure 4, strongly contributed to the empirical assumption that masonry constructions are unsafe with respect to seismic actions, being replaced by reinforced concrete and steel (materials which possess significant strength under tension) for most load bearing structures.

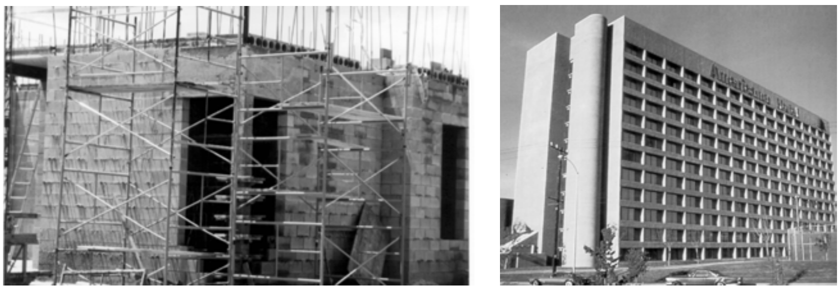
(a) (b) (c)

Figure 4: Images of devastating effects of earthquakes: (a) San Francisco, USA (1906), (b) Messina, Italy (1908) and (c) Tokyo, Japan (1923).

The experience of developed countries in the last years – e.g. Loma Prieta, USA (1989) or Kobe, Japan (1995) – demonstrates that modern structures, built with masonry, reinforced concrete or steel, according to the present codes, might still suffer important damage or collapse due to different causes. Structural and earthquake engineers must learn from these lessons in order to design and built structures with adequate economy and safety levels. Nevertheless, experience has demonstrated that, in general, unreinforced masonry exhibits poor performance when subjected to seismic actions. In earthquake prone areas, its use is only recommended for low-rise buildings. On the contrary, confined masonry (masonry built inside reinforced concrete or reinforced masonry elements, not intended to perform as a moment resistant frame, on all four sides) and reinforced masonry (masonry in which bars or mesh, usually of steel, are embedded in mortar or grout so that all materials act together in resisting forces) seems to exhibit excellent behavior with respect to seismic actions [6,7]. It is also stressed that existing constructions retrofitted according to anti-seismic provisions seem to exhibit adequate behavior.

2.2. Load bearing masonry walls in the 20th century

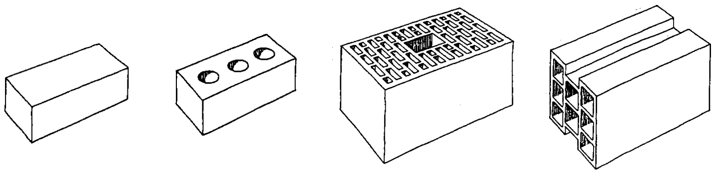
The current application of structural masonry in developed countries is marginal, even if some exceptions exist. For example, in Switzerland, the use of structural masonry increased significantly with the development of a new code of practice and full characterization of materials suitable for structural applications; in USA, reinforced and prestressed masonry are competitive solutions, see Figure 5; and in the Netherlands maxi-blocks, with length of 1.0 m, are produced aiming at building automation.



(a) (b)

Figure 5: In USA grouted structural masonry walls are common: (a) four-story building with reinforced concrete blocks masonry and prefabricated slab panels, and (b) twelve-story hotel with reinforced masonry: double leaf with external ceramic bricks.

The techniques and materials used to build masonry structures show large variation from one country to another, even if some trend towards standardization has been observed in the last years. Nevertheless, the costs involved in the transportation of materials, production technology transfer and the background of technicians, still allow for a wide range of products. This heterogeneity is responsible for additional difficulties in the wide use of load bearing masonry walls. Ceramic brick is the most used material for the masonry units but concrete or calcium-silicate blocks are also common. Even for the same material, numerous shapes are available, see Figure 6.



(a) (b) (c) (d)

Figure 6: Schematic representation of ceramic masonry units: (a) solid unit, (b,c) perforated units and (d) hollow tiles.

2.3. Innovation

A key aspect in innovation is aesthetics, as brick and block masonry can be used without rendering, see Figure 7a. This calls for increased cooperation between material scientists, architects and civil engineers, so that new shapes, textures, colours and, in the end, masonry solutions can be combined with efficient and quality-enhanced constructions technologies. Another aspect is the usage of materials that reduce cost, due to the reduction of man-labour and to increasing geometric accuracy, such as the use of rectified clay units and special purpose mortars, see Figure 7b. Also new techniques for reinforced masonry seem to be of relevance, e.g. Figure 7c. Finally, among other innovations, the new energy requirements for buildings with respect to reduction of CO2 emission (enEV2001), represent a unique opportunity to give a new strength to the masonry market.

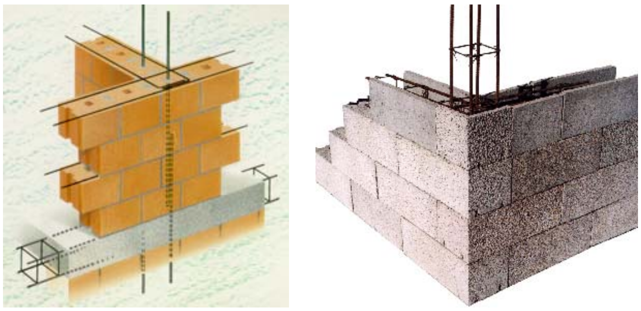
3. EXPERIMENTAL ISSUES IN MASONRY MECHANICS

Masonry is a heterogeneous material that consists of units and joints. Units are such as bricks, blocks, ashlars, adobes, irregular stones and others. Mortar can be clay, bitumen, chalk, lime/cement based mortar, glue or other. The huge number of possible combinations generated by the geometry, nature and arrangement of units as well as the characteristics of mortars raises doubts about the accuracy of the term “masonry”. Nevertheless, most of the advanced experimental research carried out in the last decades has concentrated in brick / block masonry and its relevance for design. Accurate modelling requires a thorough experimental description of the material. Next, special attention is given to displacement-controlled tests of relevance for seismic purposes and the reader is referred to [10,11] for a more comprehensive discussion on these issues.

3.1. Properties of unit and mortar

The properties of masonry are strongly dependent upon the properties of its constituents. Compressive strength tests are easy to perform and give a good indication of the general quality of the materials used. Experiments about the uniaxial post-peak behaviour and about the biaxial behaviour of bricks and blocks are less common in the literature, together with tests on cyclic behaviour. Next, some results for clay bricks under uniaxial compression [12] are briefly reviewed. A series of unloading-reloading cycles were performed in clay specimens, particularly in the post-peak region, to acquire data about stiffness degradation and energy dissipation. The experimental set-up, testing conditions and typical stress-strain diagrams are illustrated in Figure 8. The need for circumferential displacement control is stressed, and the results shown are rather difficult to obtain due to very high strength and brittleness of the units used in the testing program. The response indicates an important and monotonic decrease in Young's modulus in the post-peak regime, associated with damage growth in the material.

(a) (b)



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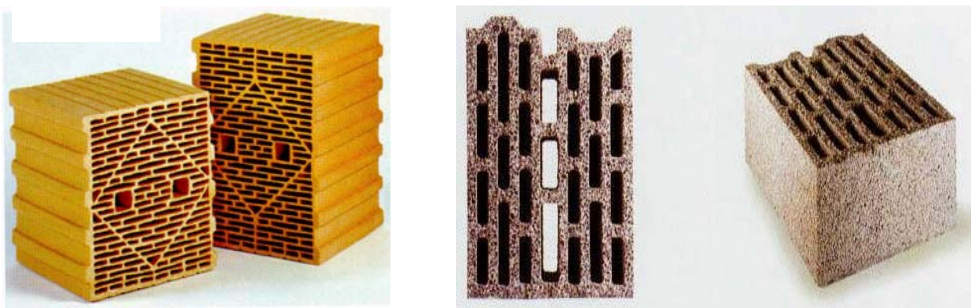
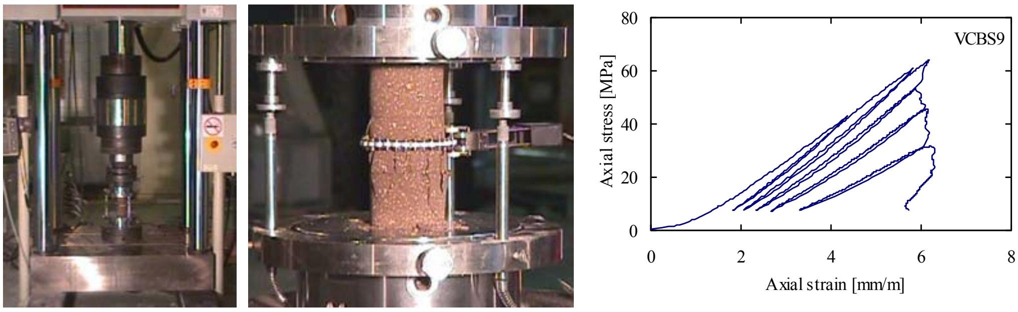


(d)

Figure 7: Some aspects of innovation: (a) aesthetics, (b) rectified units, (c) reinforced masonry, and (d) energy saving engineered units.

With respect to the tensile strength of the masonry unit, extensive information on the tensile strength and fracture energy of units can be found in [13,14]. The difficulties in relating the tensile strength of the masonry unit to its compressive strength are well known, not only due to the different shapes of the units but also to the different materials.



(a) (b) (c)

Figure 8: Aspects related to the cyclic behaviour of masonry units under uniaxial compression: (a) test set-up in universal testing machine, (b) cylindrical brick specimen under testing conditions, and (c) typical stress-strain diagram.

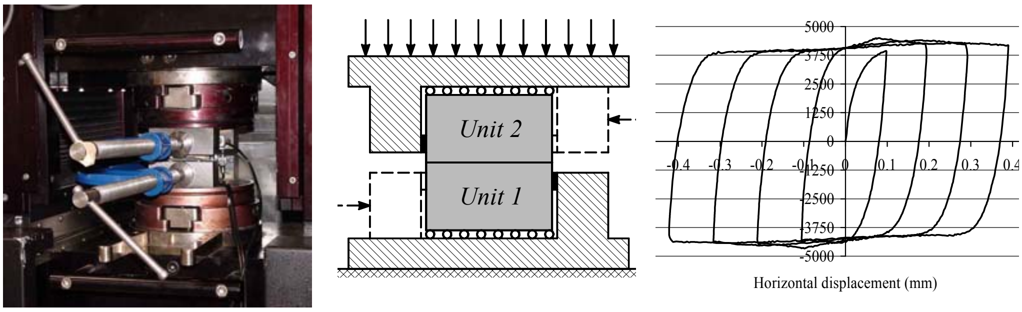
For the mortar, standard test specimens are cast in steel moulds and the water absorption effect of the unit is ignored, being thus non-representative of the mortar inside the composite. Recently, investigations in mortar disks extracted from the masonry joints have been carried out in order to fully characterize the mortar behaviour, with moderate success [15,16].

3.2. Properties of the interface

Bond between unit and mortar is often the weakest link in masonry assemblages. The non-linear response of the joints, which is then controlled by the unit-mortar interface, is one of the most relevant features of masonry behaviour. Two different phenomena occur in the unit-mortar interface, one associated with tensile failure (mode I) and the other associated with shear failure (mode II). Different test set-ups have been used for the characterization of the tensile behaviour of the unit-mortar interface.

For the purpose of numerical simulation, direct tension testing should be adopted because it allows for the full representation of the stress-displacement diagram and yield the correct strength value. No tests seem to be reported with respect to the behaviour of the interface under cyclic tensile behaviour.

A discussion about the adequacy of different test configurations for shear testing will not be given here. To obtain post-peak characteristics, the stress normal to the bed joint must be kept constant and the couplet test is more appropriate for displacement control. Adequate characterization of masonry shear behaviour under cyclic loading is given in [17,18]. The specimens of [18] consist of couplet tests, as shown in Figure 9. The experimental set-up has been designed so that the bending effects associated with shear testing are minimized. The vertical confining pressure is kept constant while the test is carried out under horizontal displacement control. Almost zero dilatancy has been found during each cycle. The tests indicate that the shear inelastic deformation is fully plastic (or irreversible).



(a) (b) (c)

Figure 9: Aspects related to the cyclic behaviour of masonry joints under shear: (a) test set-up in universal testing machine, (b) specimen under testing conditions, and (d) typical stress-strain diagram.

3.3. Properties of the composite material

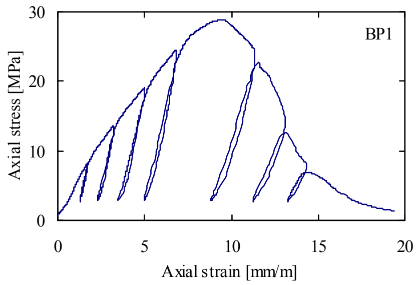
The compressive strength of masonry in the direction normal to the bed joints has been traditionally regarded as the sole relevant structural material property. The RILEM test [19] seems to return the true uniaxial compressive strength of masonry. Since the pioneering work of Hilsdorf [20] it has been accepted by the masonry community that the difference in elastic properties of the unit and mortar is the precursor of failure. Uniaxial compression tests in the direction parallel to the bed joints have received substantially less attention from the masonry community.

For tensile loading perpendicular to the bed joints, masonry strength can be generally equated to the tensile bond strength between the joint and the unit, or the tensile strength of the unit, whichever is the lowest. For tensile loading parallel to the bed joints, a sophisticated direct tension test program was set-up [21], where two different types of failure have been obtained: stepped cracks through head and bed joints or cracks running almost vertically through the units and head joints. In all cases, the strength degradation has been fully characterized.

The influence of the biaxial stress state has been investigated up to peak stress to provide a biaxial strength envelope, which cannot be described solely in terms of principal stresses because masonry is an anisotropic material. Basically, two different test set-ups have been utilized, uniaxial compression oriented at a given angle with respect to the bed joints [22] and true biaxial loading at a given angle with respect to the bed joints [23,24].

Next, some results for masonry specimens under uniaxial compression [12] are briefly reviewed. A series of unloading-reloading cycles were performed, particularly in the post-peak region, to acquire data about stiffness degradation and energy dissipation. The typical failure and stress-strain diagrams are illustrated in Figure 10. Apart from the initial adjustment between the prism and the machine platens, stress-strain curves exhibited a pre-peak bilinear behaviour, which has been reported by other authors. An initial linear branch was followed by another branch up to near the peak, with lower stiffness and greater development. The response clearly indicates an important and monotonic decrease in Young’s modulus in the post-peak regime, associated with damage growth in the material.

(a)



(b)

Figure 10: Aspects related to the cyclic behaviour of masonry specimens under uniaxial compression: (a) typical failure of masonry specimen and (c) typical stress-strain diagram.

3.4. In conclusion: Research needs at experimental level

In general, there is a need for tests of specimens under *fatigue* loading, *durability* tests coupled with mechanical tests, *shrinkage* and *creep* tests, and *non-destructive testing* (for the assessment of existing structures and quality control). In addition, the following information on constitutive behaviour under *cyclic* loading is missing:

- Masonry units subjected to tension;
- Mortar specimens, extracted from the joints,;
- Masonry joints subjected to tension;
- Biaxial behaviour of masonry.

4. NUMERICAL ISSUES IN MASONRY MECHANICS

Masonry is a material exhibiting distinct directional properties due to the mortar joints, which act as planes of weakness. Depending on the level of accuracy and the simplicity desired, it is possible to use the modelling strategies shown in Figure 11. One modelling strategy cannot be preferred over the other because different application fields exist for micro- and macro-models. Micro-modelling studies are necessary to give a better understanding about the local behaviour of masonry structures. This type of modelling applies notably to structural details. Macro-models are applicable when the structure is composed of solid walls with sufficiently large dimensions so that the stresses across or along a macro-length will be essentially uniform. Clearly, macro modelling is more practice oriented due to the reduced time and memory requirements as well as a user-friendly mesh generation. This type of modelling is most valuable when a compromise between accuracy and efficiency is needed.

It is noted that different levels of sophistication can also be adopted to create structural models. Next, a brief revision is made regarding analytical models using structural component models (a macro-modelling approach), finite element continua structural models (a macro-modelling approach) and discontinuum structural models (a micro-modelling approach).

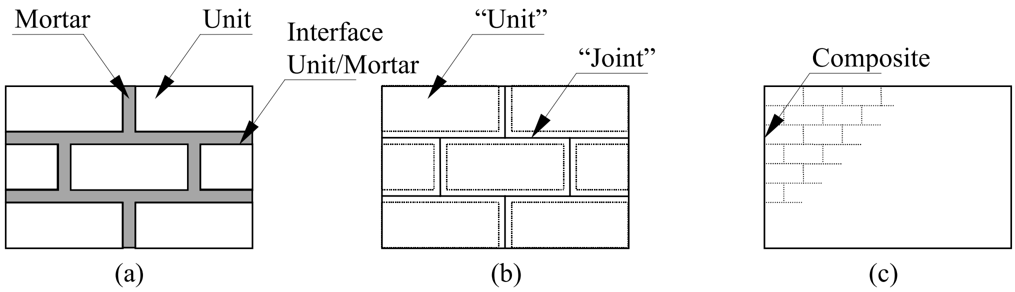


Figure 11: Modelling strategies for masonry structures: (a) masonry specimen, (b) micro-modelling and (c) macro-modelling.

4.1. Structural component models

The simplest approach to the modelling of structures is given by the application of different elements resorting to truss, beam, panel, plate or shell elements to represent columns, piers, walls, slabs, etc. Figure 12 illustrates various possibilities to model a wall with openings using structural component models, namely a lumped mass approach, a beam approach and a panel macro-model, see also [25].

The lumped approach or mass-spring-dashpot model of Figure 12b is at best a crude approximation of the actual geometry of the structure, using floor levels and lumped parameters as structural components. The simplicity of the geometric model allows increased complexity on the loading side and in the non-linear dynamic response. It can be used to determine overall dynamic structural response to actual earthquake ground motion input but rely heavily on the correct definition of component hysteresis, which has to include material non-linearity and also effects resulting from the true geometry of the structure. Such a model cannot be used to predict local or global failure mechanisms or damage levels in individual structural components. A lumped example for masonry structures is the inverted pendulum approach, which aims at studying the response of rigid block mechanism under seismic loading, see Figure 13.

The structural component model in Figure 12c approximates the actual structural geometry more accurately by using beams and joints as structural components. This approach allows to assess the system behaviour with more detail. In particular, it is possible to determine the sequential formation of local, predefined failure mechanisms and overall collapse, both statically and dynamically. The increased geometric complexity (associated with a larger number of degrees-of-freedom) makes the use of non-linear dynamic time history analysis unwieldy. Many computer codes are readily available for the use of truss and beam elements, either in 2D or 3D. Simplified collapse load analysis can be carried out, such as in [26] for the analysis of infilled masonry frames.

Finally, the structural model in Figure 12d approximates the actual structural geometry even more accurately by panel macro-elements as structural components. Rigid or deformable macro-elements have been used extensively for modelling walls and wall panels, resulting in an overall 2D or 3D model with moderate number of degrees-of-freedom. Various formulations have been proposed, namely [27], in which square damageable rigid macro-elements are adopted for incremental in plane loading, and [28], in which rigid blocks of variable form are adopted for kinematic limit analysis.

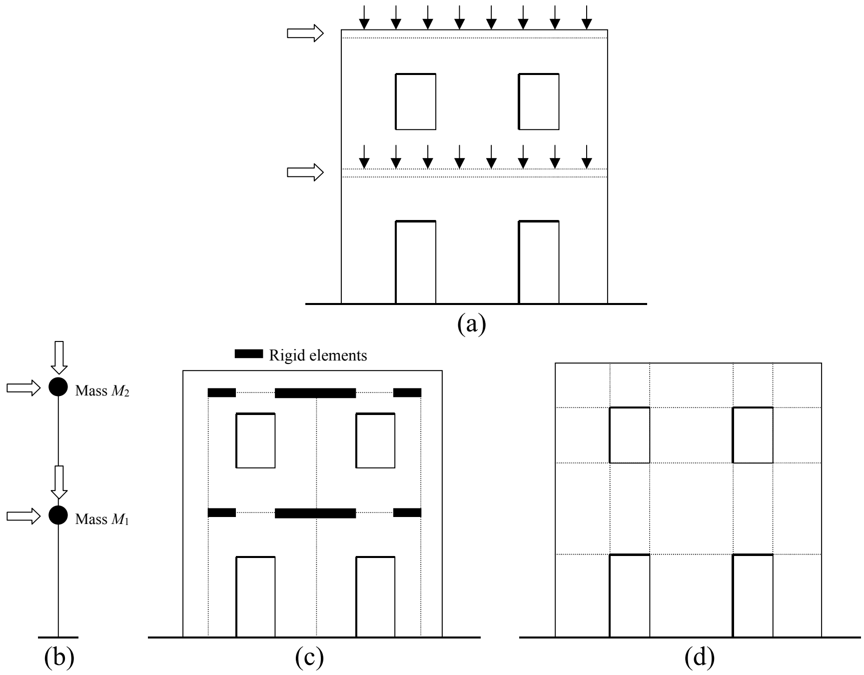


Figure 12: Examples of structural component models for (a) wall with openings: (b) lumped parameters; (c) beam elements; (d) macro-elements (rigid or deformable).

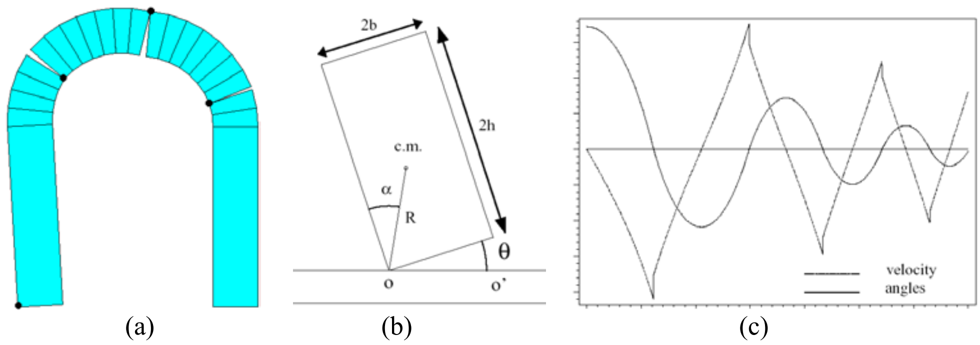


Figure 13: Inverted pendulum problem: (a) collapse mechanism, (b) rocking motion and (c) free vibration response.

Even if important developments occurred regarding consistent formulation of compatibility and equilibrium along element boundaries, as well as, regarding validation of the proposed tools with respect to valuable experimental data, inadequate selection of structural component models might yield unacceptable large errors. Thus, it must be stressed that a lot of engineering intuition, structural understanding and experimental data must be employed to formulate and use reliable structural component models and associated analysis tools.

4.2. Finite element models for continua (Macro-modelling)

Difficulties of conceiving and implementing macro-models for the analysis of masonry structures arise especially due to the fact that almost no comprehensive experimental results are available (either for pre- and post-peak behaviour), but also due to the intrinsic complexity of formulating anisotropic inelastic behaviour. Only a reduced number of authors tried to develop specific models for the analysis of masonry structures [29-32], always using the finite element method. Formulations of isotropic quasi-brittle materials behaviour consider, generally, different inelastic criteria for tension and compression. The model introduced in [31], recently extended to accommodate shell masonry behaviour [33], combines the advantages of modern plasticity concepts with a powerful representation of anisotropic material behaviour, which includes different hardening/softening behaviour along each material axis.

Figure 14 shows the results of modelling a shear wall with an initial vertical pre-compression pressure. The horizontal force *F* drives the wall to failure and produces a horizontal displacement *d* at top. The wall is confined by two concrete slabs (top and bottom) and two masonry flanges (left and right). This confinement and the large size of the wall make it appropriate for continuum modelling. Initially, cracking occurs well distributed in the panel and finally concentrates in a single shear band from one corner of the panel to the other. The compressive stresses are well below the crushing strength of masonry, i.e. failure is dominated by tension. A complete discussion of the numerical results has been given in [31].

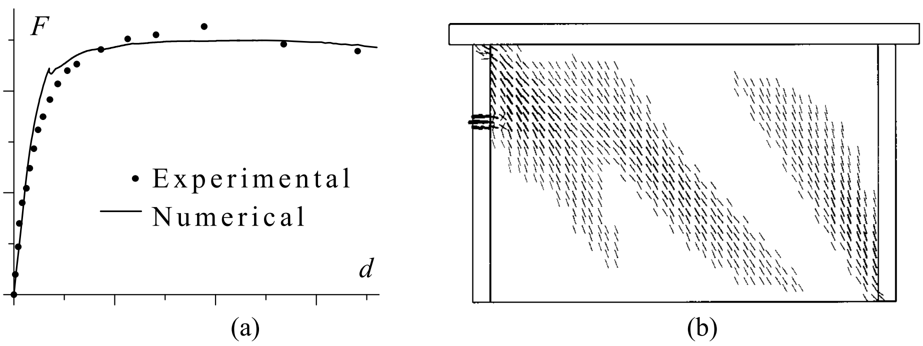
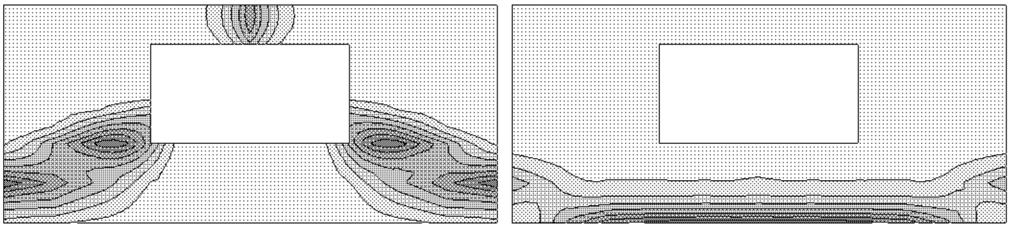


Figure 14: Results for an analysis of a masonry shear wall (macro-modelling): (a) load-displacement diagram; (b) predicted cracking pattern at ultimate load.

Figure 15 shows the results of modelling a panel with out-of-plane pressure. The panel is simply supported on two sides (left and right), fully clamped on one side (bottom) and free on the other (top). The central opening simulates a window and the panel was loaded with an air bag with a uniformly distributed load. The predicted form of collapse includes diagonal cracks from each lower corner of the panel up to the opening, which were also observed in the experiments. This form of yield line collapse does not mean that yield line design is safe due to the quasi-brittle behaviour of the material, see . A complete discussion of the numerical results has been given in [33].



(a) (b)

Figure 15: Results for an analysis of a panel subjected to uniform out-of-plane loading (macro-modelling): predicted cracking pattern at (a) bottom and (b) top face of the panel.

Modelling the behaviour of regular masonry assemblages, the typical case being brick walls, may also be addressed by homogenisation techniques. A first, powerful, approach is to handle the brickwork structure of masonry by considering the salient features of the discontinuum within the framework of a generalized / Cosserat continuum theory [34]. A second approach is to apply rigorously the homogenisation theory for periodic media to the basic cell, i.e. to carry out a single step homogenisation, with adequate boundary conditions and exact geometry [35]. The last, and most used, approach aims at substituting the complex geometry of the basic cell by a simplified geometry so that a close-form solution of the homogenisation problem is possible [36,37].

4.3. Discontinuum models (Micro-modeling)

Masonry joints act as planes of weakness and the explicit representation of the joints and units in a numerical model seems a logical step towards a rigorous analysis tool. This kind of analysis is particularly adequate for small structures, subjected to states of stress and strain strongly heterogeneous, and demands the knowledge of each of the constituents of masonry (unit and mortar) as well as the interface. In terms of modelling, all the non-linear behaviour can be concentrated in the joints and in straight potential vertical cracks in the centreline of all units. In general, a higher computational effort ensues, so this approach still has a wider application in research and in small models for localized analysis. Applications can be carried out using finite elements [38,39], discrete elements [40,41] or limit analysis [42,43].

The salient characteristics of discrete elements are: (a) rigid or deformable (combined with the finite element method) blocks; (b) connection between vertexes and sides / faces; (c) interpenetration possible, integration of the equation of motion (explicit formulation); (d) real damping coefficient (dynamic problem) or artificially high damping (static solution). The main advantages of the technique are adequate formulation for large displacements (contact update), and independent meshes for each deformable block. The main disadvantages are that a high number of contact points is needed for accurate representation of tractions in the interface, and the time requirements are rather high for large meshes, namely for 3D problems.

The salient characteristics of limit analysis are: (a) rigid blocks; (b) interpenetration not allowed; (c) mathematical formulation that leads to an optimisation problem (linear or non-linear). The main advantages of the technique are adequate formulation for design problems (requires a low number of parameters) and fast analysis. The main advantages are that only the collapse load and mechanism can be obtained, tensile strength cannot be included in the analysis, and the introduction of the loading history remains a challenge.

A complete micro-model must include all the failure mechanisms of masonry, namely, cracking of joints, sliding over one head or bed joint, cracking of the units and crushing of masonry, as in [39]. Figure 9 shows the results of modelling a shear wall with an initial vertical pre-compression pressure. The horizontal force F drives the wall to failure, keeping the top and bottom boundaries fully constrained, and produces a horizontal displacement d at top. Initially, two horizontal cracks develop at the top and bottom of the wall but at failure a diagonal stepped crack and crushing of the compressed toes are found. A complete discussion of the numerical results has been given in [39].

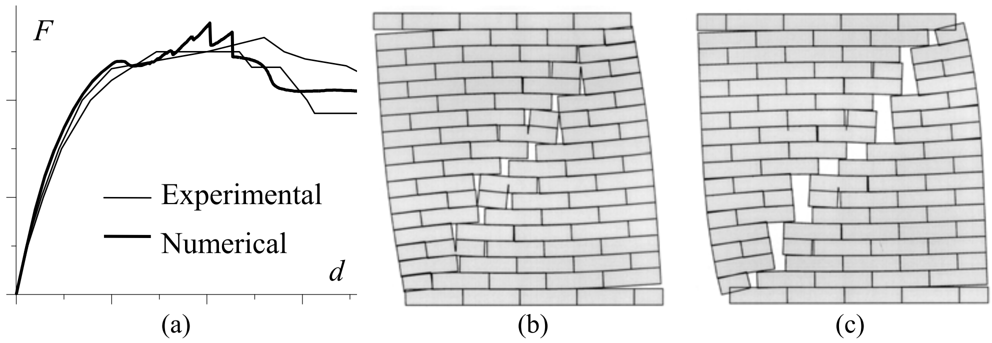


Figure 16: Results for an analysis of a shear wall (micro-modelling): (a) force-displacement diagram; (b,c) deformed meshes at peak and ultimate load.

The extension of the above model to include cyclic behaviour is given in [12]. To include non-linear unloading/reloading behaviour in an accurate fashion, new yield surfaces are introduced in the above monotonic model. In the proposed model, the motion of the unloading surfaces is controlled by a mixed hardening law. By adopting appropriate evolution rules, it is possible to reproduce non-linear behaviour during unloading, see Figure 17.

The recent experimental work in the cyclic behaviour of interfaces described in the previous chapter has shown some important characteristics, namely stiffness degradation in both tension and compression regimes, residual relative displacements at zero stress, absence of stiffness degradation in direct shear, and complete crack closing under compressive loading. The available experimental results concerning the cyclic behaviour of interfaces suggest that: (a) Elastic behaviour constitutes a satisfactory approach for shear unloading/reloading behaviour; (b) Elastic unloading/reloading is not an appropriate hypothesis for tensile and compressive loading since observed experimental behaviour cannot be simulated accurately, namely stiffness degradation and crack closing/reopening, which clearly exhibit non-linear behaviour.

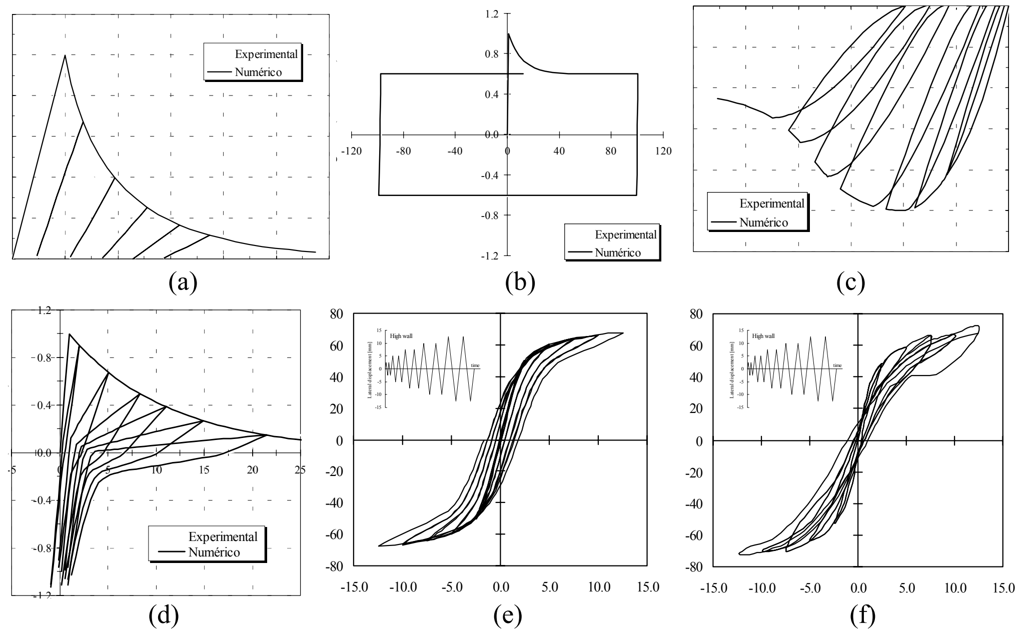


Figure 17: Experimental vs. numerical behaviour for an interface model extended to cyclic formulation: (a) tensile behaviour; (b) shear behaviour; (c) compression behaviour; (d) tension-compression behaviour; (e,f) shear walls (numerical results on the left).

The examples above demonstrate the power of modern numerical tools to represent the complex interaction between masonry components (units and joints). Both, the response of plane and three-dimensional structures controlled by the local behaviour of masonry, and difficult phenomena observed in the experiments can be reproduced.

4.4. In conclusion: Research needs at modelling level

In general, there is a need for incorporation of physical, chemical and mechanical *deterioration* in the existing models. In addition, the following advances are of particular relevance:

- Non-linear behaviour coupled with micro-mechanical homogenisation techniques;
- Solving the ill-posedness of non-linear formulations of quasi-brittle materials;
- Reliable set of rules for the definition of macro-blocks in masonry.

5. CONCLUSIONS

Significant knowledge is available in the context of modern testing and advanced analysis of masonry structures. Constraints to be considered in the use of advanced modelling are the cost, the need of an experienced user / engineer, the level of accuracy required, the availability of input data, the need for validation and the use of the results. Obtained results are usually important for understanding the structural behaviour of the constructions. But, as a rule, advanced modelling is only necessary in practice to understand the behaviour and damage of (complex) constructions and to assist in the definition of rational design rules, based on a reliable and economical numerical laboratory. The key message of the paper is that research and innovation are strongly needed to assess the vulnerability of existing constructions, to define economical rational design rules, to allow for bold, novel shapes and novel applications of masonry, and to contribute to masonry innovation. Without the latter, the masonry market will inevitably shrink in the future.

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